



# Effect of an innovative sorbent material coupled to continuous flow process in the protein and oxidative stability of white wines

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## ABSTRACT

In this work the impact of an innovative protein stabilization method (TiO<sub>2</sub>-based composite sorbent material coupled with a prototype device operating under continuous flow) has been tested in terms of protein and oxidative stability of white wines. Optimal process parameters (duration 60 min; flow rate 1.5 ± 0.1 L/h in 6 cycle rates/h) ensured an average 32.5 % reduction of total proteins; the nanoporous TiO<sub>2</sub> film supported on inert glass beads acted as selective sorbent for pathogenesis-related proteins (PRPs, 10–60 kDa) responsible for wine instability, based on the protein stability studies (heat-test) performed in the experimental wines. The stabilization process has been tested for the release of contaminants (TI), and the innovative treatment has been proven to preserve wine from oxidation also delaying the browning onset under extreme storage conditions.

## 1. Introduction

The stability of bottled wines is a major concern for oenologists, especially for exported wines which might undergo stressful condition of storage and transport, in particular high temperature, along the supply chain (Ubeda et al., 2020). Among the causes of wine instability, the protein haze is a main issue in white wines and depends on several factors that elicit certain specific grape proteins to cause haze or precipitation of insoluble material in wine. The so-called “pathogenesis-related proteins” from grape (PRPs, mainly thaumatin-like proteins and chitinases) - with a molecular weight between 10 and 60 kDa and an isoelectric point (Ip) below 6 - are the main responsible of the problem (Marangon et al., 2014).

The most used problem-solving approach includes protein stability tests (e.g., heat-test, Bentotest®) to determine a wine's intrinsic tendency to develop turbidity, and a batch treatment to remove PRPs before bottling of potentially unstable wines (Sarmiento et al., 2000a; Pargoletti et al., 2021). Regardless many coadjuvants and technological solutions have been studied in recent years - including the use of zirconia (Lucchetta et al., 2013), magnetic nanoparticles (Mierczynska-Vasilev et al., 2019), composite materials (Marangon et al., 2011), grape seed extracts (Romanini et al., 2021), among others - the fining of wine with bentonite is still the treatment of choice to remove unstable proteins from white

wines (Pargoletti et al., 2021; Sommer & Tondini, 2021). Regrettably, the treatment with bentonite affects wine composition, and entails both waste disposal and some product loss due to a time-consuming discontinuous process that involve the gravity settling and subsequent racking/filtering of wine (Sommer & Tondini, 2021).

Remarkable studies on the use of percolated beds for the continuous stabilization of wines, despite failing to identify a suitable resin for oenological applications, have provided a benchmark methodological approach to the problem (Sarmiento et al., 2001b). In this view, we recently developed a patent (Patent No. 102018000004721; PCT/IB2019/053102) on a laboratory-scale approach for the stabilization of white wines with a device operating under continuous flow regime and including a packed column with nanoporous titanium dioxide composite (TiO<sub>2</sub>) thin film as the sorbent material supported on inert glass beads. The innovation lies in the possibility of using an affordable material, reusable in several treatment cycles, under operational conditions suitable for industrial upgrading. Nanostructured materials are becoming increasingly important in the food industry, and their introduction as winemaking coadjuvants has recently been suggested (Gil-Sánchez et al., 2019); in this work, TiO<sub>2</sub> was chosen for protein stabilization because of its high chemical affinity with proteins combined with high engineering potential (Vian et al., 2021). Different proteins structure can affect the mechanisms of adsorption on nanostructured TiO<sub>2</sub>; nevertheless, there is

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a consensus in the literature about the electrostatic interactions between negatively charged groups on the TiO<sub>2</sub> nano-surface and positively charged surface of the proteins, i.e., the charged amino group, being the main responsible for adsorption (Vian et al., 2021). This mechanism was further corroborated by recent studies investigating, among others, the adsorption of chitinase-like proteins which are widely recognized as the main responsible for wine instability (Dawes et al., 1994; Marangon et al., 2011; Lucchetta et al., 2013), on the negatively-charged TiO<sub>2</sub> nanoparticles (Poulsen et al., 2023); in more detail, according to Poulsen et al. (2023), the adsorption of chitinase-like proteins on TiO<sub>2</sub> nano-structures can be favored by a combination of hydrophobics and electrostatics interaction.

Further studies have examined surface modifications of TiO<sub>2</sub> (i.e., hydroxylation) to explore the possibility of modulating adsorption, concluding that the acidic and basic residues show great affinity in both hydroxylated and non-hydroxylated TiO<sub>2</sub> surfaces (Kang et al., 2010). Structural size, on the other hand, plays a crucial role in the extent and selectivity of adsorption. When moving from micro to nanostructured TiO<sub>2</sub>, the binding of proteins maintains an essentially electrostatic character with the pH, the protein charge, and the solution ionic strength as the driving forces (Topoglidis et al., 2001a). Nevertheless, a few interesting changes occur in the adsorption process: firstly, the active surface available for protein binding over the geometrical area is greatly enhanced by increasing the thickness of the nanoporous film, for instance, by a factor of 850 for an 8 µm thick film (Topoglidis et al., 2001b). Secondly, when considering a nanoscaled surface topography, dimensionality of the surface roughness greatly influences the protein adsorption capacity, along with surface chemistry and concentration of adsorbed proteins. Rechenndorff et al. (2006), found that the surface roughness impacts the wettability, leading to a local change in surface chemistry and a restricted access to proteins, which undergo different degrees of geometrical packing at the TiO<sub>2</sub> surface. In addition, the effect of surface curvature, coupled with protein configuration (globular, linear) plays an important role on the selectivity of adsorption (Roach et al., 2005).

A recent EU regulation (COMMISSION DELEGATED REGULATION (EU) 2020/217) has temporarily rehabilitated titanium oxide in terms of food safety, and TiO<sub>2</sub> nanoparticles seems to have great therapeutic potential for cancer treatment (Zarzzeka et al., 2023). Although OIV allow the use of ceramic membranes with titanium oxide for ultrafiltration of wine (OIV COEI-1-MEMULT - Ultrafiltration membranes), the photocatalytic activity of TiO<sub>2</sub> (Schneider et al., 2014) requires a careful evaluation in terms of side effect on the physicochemical stability of wines.

In this work, potentialities and limitation of the innovative treatment were explored. Model wine solutions and unstable white wines were treated using a laboratory-scale prototype working at flow regime. At first, performances in terms of protein removal capacity and wine stabilization were assessed. The extent of titanium released following the treatment and under oenological conditions has been assessed, and the physico-chemical stability of the wines has been evaluated in terms of their susceptibility to oxidation.

## 2. Materials and methods

### 2.1. Wines and model wine solutions

Commercial monovarietal Muller Thurgau vintage 2019 and Gewürztraminer vintage 2021 white wines were obtained from Italian wineries. The fermentation was carried out at industrial scale where wines were clarified by gravity alone without any additional stabilization coadjuvant/treatment; then samples were delivered to the laboratory for the experiments (Table 1). Wines were selected based on preliminary screening of potential protein instability.

In addition, model wine solutions (Table 1, samples no. 8–10) were prepared to estimate the extent of Ti released during the process. The

**Table 1**  
Wine/model wine codes and description.

Sample no.	Sample code	Sample description	Experiment	
1	MT-filtr	Muller Thurgau with 0.45 µm CA filtration	Optimization of the protein stabilization process	
2	MT-flowTiO <sub>2</sub>	Muller Thurgau protein stabilized with continuous TiO <sub>2</sub> treatment + 0.45 µm CA filtration (treatment duration)		
3	MT-batchTiO <sub>2</sub>	Muller Thurgau protein stabilized in batch (24 h, 175 beans/L wine) + 0.45 µm CA filtration	TiO <sub>2</sub> migration tests	
4	GT-filtr	Gewürztraminer with 0.45 µm CA filtration		
5	GT-beads-filtr	Gewürztraminer fluxed over bare glass beads + 0.45 µm CA filtration		
6	GT-flowTiO <sub>2</sub>	Gewürztraminer protein stabilized with continuous TiO <sub>2</sub> treatment + 0.45 µm CA filtration		
7	GT-batchTiO <sub>2</sub>	Gewürztraminer protein stabilized in batch (24 h, 175 beans/L wine) + 0.45 µm CA filtration		
8	mws-filtr	Model wine solution with 0.45 µm CA filtration		
9	mws-beads-filtr	Model wine solution fluxed over bare glass beads + 0.45 µm CA filtration		
10	mws-TiO <sub>2</sub>	Model wine solution + TiO <sub>2</sub> – glass composite + 0.45 µm CA filtration		
11	GT-filtr-t0	Same WCtrl-1G wine		Shelf-life assay (Oxidative stability, oxidability tests and oxidation kinetics)
12	GT-beads-filtr-t0	Same WCtrl-2G wine		
13	GT-flowTiO <sub>2</sub> -t0	Same Wtr-G wine	Shelf-life assay (Oxidative stability, oxidability tests and oxidation kinetics)	
14	GT-batchTiO <sub>2</sub> -t0	Same Batch-G wine		
15	GT-filtr-t20L	WCtrl-1G wine after 20 days heat (35 °C) and daylight exposure		
16	GT-beads-filtr-t20L	WCtrl-2G wine after 20 days heat (35 °C) and daylight exposure		
17	GT-flowTiO <sub>2</sub> -t20L	Wtr-G wine after 20 days heat (35 °C) and daylight exposure		
18	GT-batchTiO <sub>2</sub> -t20L	Batch-G wine after 20 days heat (35 °C) and daylight exposure		
19	GT-filtr-t20D	WCtrl-1G wine after 20 days heat (35 °C) in dark		
20	GT-beads-filtr-t20D	WCtrl-2G wine after 20 days heat (35 °C) in dark		
21	GT-flowTiO <sub>2</sub> -t20D	Wtr-G wine after 20 days heat (35 °C) in dark		
22	GT-batchTiO <sub>2</sub> -t20D	Batch-G wine after 20 days heat (35 °C) in dark		

model wine was made up of 12 % v/v ethanol (>99 %) in distilled water, with the addition of L-tartaric acid 0.033 M and NaOH 1 M to reach pH 3.6; reagents grade chemicals and solvents were used without further purification (Merck, Darmstadt, DE).

### 2.2. Physical properties of the sorbent material

A detailed characterization of the composite sorbent material is provided in the Patent application (Patent No. 102018000004721; PCT/

IB2019/053102). Briefly, it consists of a thin layer of TiO<sub>2</sub> nanoparticles sintered onto 5 mm diameter inert glass beads. The TiO<sub>2</sub> layer was obtained using a *sol-gel* process, with *sol* consisting of a colloidal suspension of TiO<sub>2</sub> nanoparticles, deposited on glass spheres through *dip coating* (immersion). Evaporation of the solvent induced the rapid formation of a thin layer of amorphous gel, which was dried and heat-treated up to 500 °C.

The sintered TiO<sub>2</sub> active film exhibits the following characteristics: 2 μm thickness, nanostructured and porous surface made up of spherical particles with a diameter of 20–30 nm, porous structures with a 50 nm average diameter. According to the sol characteristics, the TiO<sub>2</sub> layer has a BET surface area ranging 90–100 m<sup>2</sup>/g, and a pore sorbent volume of 0.40–0.50 cm<sup>3</sup>/g (Patent No. 102018000004721; PCT/IB2019/053102).

### 2.3. Continuous wine stabilization

A detailed description of the prototype device operating under continuous flow is provided in the Patent application (Patent No. 102018000004721; PCT/IB2019/053102). In this experiment, wines were treated by a continuous process using the TiO<sub>2</sub>-based sorbent material packed in a 330 mm high column with an internal diameter of 25 mm. Stabilization of a unit volume of wine (1 L) was obtained by filling the column to its maximum capacity (175 ± 10 g of composite beads). The wine was pumped from the feed tank to the column through plastic tubes by up-flow mode at a flow rate of 1.5 ± 0.12 L/h, corresponding to 6 cycle rates/h and continuously recircled using a peristaltic pump. These preliminary process parameters are suited to a lab-scale experiment and need to be tailored for further industrial applications. Five processing times (10, 20, 30, 60 and 120 min) were considered in recirculation mode through the stabilization device to set the optimum duration of the treatment. The test was performed using the Muller Thurgau wine, and after stabilization the sample was filtered through a 0.45 μm cellulose acetate (CA) (sample *MT-flowTiO<sub>2</sub>*). A control was made by the Muller Thurgau wine just filtered at 0.45 μm CA (*MT-filtr*, Table 1).

Batch experiments were performed using the same sorbent-to-wine ratio (175 beans/L wine), to assess the stabilization performances of the innovative material under static conditions (*MT-batchTiO<sub>2</sub>*, Table 1).

Once optimized, the protocol was similarly applied to the stabilization of the Gewürztraminer 2021 wine. In this experiment, along with the *GT-flowTiO<sub>2</sub>* (continuous TiO<sub>2</sub> treatment), *GT-filtr* (Gewürztraminer with simple 0.45 μm CA filtration) and *GT-batchTiO<sub>2</sub>*, a further control was added (*GT-beads-filtr*) made up of wine processed with continuous flow by adding bare glass beads in the packed column, followed by 0.45 μm CA filtration (Table 1).

The TiO<sub>2</sub> sorbent material was regenerated after every treatment by immersion in NaOH 1 M solution (60 min) and subsequent washing with distilled water until neutral pH was restored. All experiments were performed at room temperature.

### 2.4. Total protein content and protein stability of wines

The total protein content was determined using the potassium dodecyl sulfate (KDS) method (Vincenzi et al., 2005), and results were expressed using a 0–1250 mg/L BSA calibration curve.

The protein stability was evaluated applying the thermal test originally described by Pockock and Rankine (1973) with minor modifications. An AL250T-IR turbidimeter (Tintometer GmbH Division Aqualytic, Dortmund, DE) was used to determine the difference in turbidity (ΔNTU) of wine samples before and after the thermal treatment (80 °C, 30 min, followed by cooling at room temperature over 45 min). The ΔNTU was proportional to the extent of protein instability, and wines were considered stable with ΔNTU < 2.

### 2.5. Migration study

The Ti content in wine was determined in two distinctive experiments by Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-AES) at an accredited laboratory (Vassanelli Lab Srl, Bussolengo, IT) and in accordance with the official International Organisation of Vine and Wine method (OIV, 2013).

The first experiment aimed at estimating the extent of titanium release during the continuous stabilization of wine. The titanium level was determined after the flow treatment of model wine solution (*mws-TiO<sub>2</sub>*), compared to filtration alone at 0.45 μm (*mws-filtr*) and continuous flow of model wine onto bare glass spheres without titanium (*mws-beads-filtr*).

A second experiment was aimed at determining the effective release of active sorbent (TiO<sub>2</sub>) per unit weight of the composite material. Although the dosage of 175 g composite beads/L wine might appear high, the active sorbent represents only a limited fraction by weight of the composite material. As preliminary assessment, model wine was added with glass beads activated with TiO<sub>2</sub> layers and treated by ultrasonic agitation. The resulting solutions were bottled in a N<sub>2</sub> atmosphere and soon delivered for Ti analysis.

### 2.6. Wine oxidation tests

A two-stage experiment was performed on *GT-filtr*, *GT-bead-filtr*, *GT-flow-TiO<sub>2</sub>*, *GT-batch-TiO<sub>2</sub>* wines (samples no. 11–22, Table 1) to assess the impact of the treatment on the oxidation of wine. Immediately after the treatment selected physicochemical parameters of wine were measured on *GT-filtr-t0*, *GT-bead-filtr-t0*, *GT-flow-TiO<sub>2</sub>-t0*, *GT-batch-TiO<sub>2</sub>-t0*, including: free (SO<sub>2</sub>F) and total (SO<sub>2</sub>T) sulfur dioxide (Ripper, & Schmitt, 1896); the inorganic iron speciation (Danilewicz, 2016), with calibration curve made by Fe(II) in the range 0–5 mg/L; pH (HANNA 209 pHmeter, Merk, Germany); total polyphenol content (TPC<sub>280nm</sub>) expressed as mg/L gallic acid equivalents (GAE) (Ribereau-Gayon, 1970).

Thereafter, selected wines (*GT-beads-filtr*, *GT-flowTiO<sub>2</sub>*, *GT-batch-TiO<sub>2</sub>*) were subjected to accelerated ageing conditions at 35 ± 1 °C for 20 days (Ricci et al., 2017) in daylight exposure (*GT-beads-filtr-t20L*, *GT-flowTiO<sub>2</sub>-t20L*, *GT-batch-TiO<sub>2</sub>-t20L*) and dark (*GT-beads-filtr-t20D*, *GT-flowTiO<sub>2</sub>-t20D*, *GT-batchTiO<sub>2</sub>-t20D*) conditions (details in Table 1). Physico-chemical wine parameters selected to monitor the oxidation onset were: total flavan-3-ols (mg/L (+)-catechin equivalents, CE), volatile acidity (g/L acetic acid equivalents, AA) and sulfates (mg/L SO<sub>4</sub><sup>2-</sup>), determined by a Fourier Transform Mid Infrared technique (Bacchus 3 Steroglass Srl, Perugia, IT); the concentration of peroxides determined by the FOX-1 colorimetric assay (Bridi et al., 2015), with calibration curve: H<sub>2</sub>O<sub>2</sub> 0–15.7 μM. The CIELab chromatic coordinates L\*, a\*, b\*, with illuminant D65 and 10° observer (OIV, 2006) were calculated using the DNAPhone Smart Analysis technology (DNAPhone, Parma, IT). Other parameters, such as chroma (C\*<sub>ab</sub>) and hue (h<sub>ab</sub>) were calculated from the CIELab space according to the following (4), (5):

$$C^*_{ab} = \sqrt{(a^*)^2 + (b^*)^2} \quad (4)$$

$$h_{ab} = (b^*/a^*) \quad (5)$$

CIELab coordinates were further employed to estimate the Browning index (BI), according to Benucci et al. (2024) (6), (7):

$$BI = 100(x - 0.31)/0.17 \quad (6)$$

$$x = (a^* + 1.75L^*)/5.645L^* + a^* - 3.012b^* \quad (7)$$

In addition, the 420 nm optical density (OD<sub>420nm</sub>) was monitored in kinetic studies (Ricci et al., 2017) over 20 days. All colorimetric determinations were made in 10-mm glass cuvettes using a Cary 60 UV-Vis spectrophotometer (Agilent Technologies, Santa Clara, CA, US).

## 2.7. Statistical analysis and colorimetry artwork

Data are presented as mean values  $\pm$  standard deviation (SD) obtained from two replicates. Mean differences in the physico-chemical parameters of the wines were evaluated by one-way analysis of variance (ANOVA) followed by a post-hoc Tukey test to determine the statistical significance at  $p \leq 0.05$ . All the analyses were carried out using XLSTAT version 2023.1.1 (Addinsoft, Anglesey, UK).

The CIELab graph was created using RStudio –Colorspace and Ggplot2 installed locally on a Macbook Pro (macOS Catalina ver. 10.15.7).

## 3. Results and discussion

### 3.1. Continuous protein stabilization of wines

The protein stabilization experiments were performed on Muller Thurgau and Gewürztraminer unstable wines (sample no. 1–7, Table 1). The effect of continuous flow process up to 120 min for the protein stabilization of Muller Thurgau (*MT-flowTiO<sub>2</sub>*) was assessed by the heat test and measuring the protein content before and after the treatment for t60 min and t120 min (Table 2). The process required 60-min to achieve the protein stabilization of wine ( $\Delta NTU = 1.22 \pm 0.06$ ). The effect was maintained by extending the treatment up to 120 min ( $\Delta NTU = 1.11 \pm 0.08$ ) with no significant differences in the stability level achieved ( $p = 0.062$ ), thus suggesting the lack of PRPs desorption effects within the time range considered. The high reproducibility between replicates of heat test was confirmed with a batch treatment under static conditions applied for 24 h (*MT-batchTiO<sub>2</sub>*,  $\Delta NTU = 1.25 \pm 0.04$ , Table 2) using the condition of the continuous process (i.e., same sorbent-to-wine ratio and the same wine volume).

The initial protein content dropped by  $19.0 \pm 1.3\%$  after 60 min, and by  $26.2 \pm 1.1\%$  after 120 min of processing with respect to the *MT-filtr*. There was a significant difference in the total protein content between time 60 and 120 min ( $p = 0.035$ ), regardless similar protein stability ( $\Delta NTU$ ) was achieved in both wines (Table 2). The higher protein removal at time 120 min suggested that a further, secondary adsorption mechanisms is likely to occur under prolonged continuous treatment, with potential involvement of structural wine proteins, i.e., arabinogalactans and mannoproteins; this is consistent with previous reports (Lin et al., 2024) about the tendency of TiO<sub>2</sub> to enrich glycopeptides via TiO<sub>2</sub>-amino acids multiply-mesoporous hydrophilic nano-hybrid. On a similar fashion, the TiO<sub>2</sub> nanostructures of the composite material can adsorb the RPRs proteins at the first stage, thus increasing the hydrophilicity of the surface and promoting a secondary adsorption of glycans.

Given the implication of glycoproteins into different wine characteristics besides protein stability i.e., sensory, foamability (Palmisano et al., 2010), the effect of a prolonged exposure of wine to the TiO<sub>2</sub>-based sorbent material must be deepened in future proteomic studies, to

**Table 2**  
Protein stabilization trials of Muller Thurgau 2019 and Gewürztraminer 2021 wines. BSA: Bovine serum albumin.

Sample no.	Sample code	Protein content (mg/L BSA)	Heat test ( $\Delta NTU$ )
1	MT-filtr	45.8 $\pm$ 1.8	3.20 $\pm$ 0.02
2	MT-flowTiO <sub>2</sub> 60 min	37.1 $\pm$ 0.4	1.22 $\pm$ 0.06
3	MT-flowTiO <sub>2</sub> 120 min	33.8 $\pm$ 0.78	1.13 $\pm$ 0.04
4	MT-batchTiO <sub>2</sub>	35.4 $\pm$ 1.6	1.54 $\pm$ 0.28
5	GT-filtr	17.7 $\pm$ 0.6	6.87 $\pm$ 0.07
6	GT-beads-filtr	16.8 $\pm$ 1.0	5.98 $\pm$ 0.54
7	GT-flowTiO <sub>2</sub>	9.3 $\pm$ 1.1	1.36 $\pm$ 0.14
8	GT-batchTiO <sub>2</sub>	9.8 $\pm$ 0.6	1.93 $\pm$ 0.08

settle the most appropriate duration of the treatment.

The protein removal under static conditions (*MT-batch TiO<sub>2</sub>*, Table 2) was  $22.6 \pm 0.4\%$ , which is consistent with values of the continuous process. Overall, these findings suggest the presence of a selective adsorption capacity of the composite TiO<sub>2</sub> material, as the protein stability of wine ( $\Delta NTU$ ) was achieved against a small percentage of proteins removed, allegedly being the PRPs. Based on the preliminary experiments, an optimum processing time of 60 min was settled to achieve the protein stabilization of wines.

The potential contribution of process boundary conditions on the protein stability was investigated using the wine Gewürztraminer 2021 processed in continuous (*GT-flowTiO<sub>2</sub>*). In particular, the impact of the CA 0.45  $\mu\text{m}$  filtration (*GT-filtr*) and the effect of the pumping into the flow device without the sorbent TiO<sub>2</sub> layer (*GT-beads-filtr*) were evaluated. Once again, a batch treatment (*GT-batchTiO<sub>2</sub>*) was investigated for further comparison (Table 2). After 60 min of continuous treatment the *GT-flowTiO<sub>2</sub>* gained the protein stability (Table 2), with a significant reduction in the total protein content compared to the *GT-filtr* ( $-47.4 \pm 4.5\%$ ). Also, the *GT-batchTiO<sub>2</sub>* was protein-stabilized (Table 2). As expected, both *GT-filtr* and *GT-beads-filtr* remained unstable with only a slight decrease in the average total protein content in *GT-filtr* after simple 0.45  $\mu\text{m}$  CA filtration ( $-2.61 \pm 0.6\%$ ). Based upon these findings, the TiO<sub>2</sub> sorbent is the only factor affecting the protein stability of the treated wines.

### 3.2. Migration studies

The migration tests were conducted on model wine solution placed in contact with the composite material under continuous flow for 60 min (*mws-TiO<sub>2</sub>*); further tests assessed the potential contamination from the filtration (*mws-filtr*) and the reagents, glass beads and solvents used (*mws-beads-filtr*).

In detail, *mws-TiO<sub>2</sub>* ranged between 7.1 and 13  $\mu\text{g Ti/L}$  (average  $10.05 \pm 2.95 \mu\text{g Ti/L}$ ), with the maximum concentration of Ti detected corresponding to 22  $\mu\text{g/L}$  of TiO<sub>2</sub> in submicrometric form. The latter value overestimates the contribution from the composite material, as *mws-filtr* and *mws-beads-filtr* also contained 2.9 to 5.3  $\mu\text{g/L}$  trace Ti as cross-migration (*mws-filtr*  $3.05 \pm 0.15 \mu\text{g/L Ti}$ ; *mws-beads-filtr*  $4.4 \pm 0.9 \mu\text{g/L Ti}$ ). This is aligned with the effective titanium content expected in wine, as Plotka-Wasylyka et al. (2018) highlighted Ti concentrations in 44 white and red Polish wines ranging between 0.54 and 2.37  $\mu\text{g/L}$ , with a maximum limit concentration of titanium in wine set at 1 mg/L in Germany. The European Food Safety Authority (EFSA) has recently reviewed the use of titanium dioxide in the food industry (EFSA Panel, 2021), reporting that the use of the E171 food-grade TiO<sub>2</sub> should be considered with caution to ensure food safety. However, the same report states that a dosage below 1 mg/kg body weight per day of TiO<sub>2</sub> micropowder (E171) or 100 mg/kg of nanostructured TiO<sub>2</sub> (<30 nm) does not cause adverse effects. Referring to these limit values, we can conclude that the Ti/TiO<sub>2</sub> concentrations measured in this experiment are well below a threshold considered acceptable to ensure food safety. Nevertheless, while the technological effectiveness of the material is the focus of this study, further advances will require (a) engineering the material to limit further the release of nanostructures and (b) migration tests under standardized conditions to evaluate the food suitability.

Further key issues related to the adsorption process, including subsequent effective cycles of use and the regenerative capacity of the material will be the object of future investigations.

### 3.3. Wine oxidation tests

The effect of protein removal treatment was also evaluated in terms of its impact on the oxidative stability of wines. Firstly, to disclose any short-term effects which is likely to impact the shelf-life of wines, selected compositional parameters (Table 3) were monitored immediately after the flow process (samples *GT-filtr-t0*, *GT-beads-filtr-t0*,



**Table 3**

Selected compositional parameters of Gewürztraminer wine 2021 measured following the protein stabilization treatment.

	GT-filtr-t0	GT-beads-filtr-t0	GT-flowTiO <sub>2</sub> -t0	GT-batchTiO <sub>2</sub> -t0
SO <sub>2</sub> F mg/L	19 ± 0 <sup>d</sup>	7 ± 1 <sup>a</sup>	12 ± 1 <sup>b</sup>	17 ± 0 <sup>c</sup>
SO <sub>2</sub> T mg/L	47 ± 0 <sup>b</sup>	43 ± 0 <sup>a</sup>	45 ± 1 <sup>a,b</sup>	45 ± 1 <sup>a,b</sup>
Fe(III)/Fe(tot) %	0	9 ± 1 <sup>b</sup>	2 ± 1	1 ± 0
Fe(tot) µg/L	377 ± 12	358 ± 14	377 ± 18	374 ± 3
TPC <sub>280nm</sub> mg/L	329 ± 0	333 ± 1	330 ± 6	330 ± 2
GAE				
pH	3.30 ± 0.01	3.30 ± 0.01	3.29 ± 0	3.30 ± 0.01
Total peroxides µM H <sub>2</sub> O <sub>2</sub>	0.06 ± 0.02	0.09 ± 0.00 <sup>b</sup>	0.06 ± 0.00	0.05 ± 0.01
Flavan-3-ols mg/L CE	21 ± 1	22 ± 2	21 ± 1	20 ± 0
Volatile acidity g/L AA	0.24 ± 0.00	0.24 ± 0.01	0.25 ± 0.01	0.24 ± 0.00
Sulphates mg/L SO <sub>4</sub> <sup>2-</sup>	397 ± 48	385 ± 18	377 ± 4	396 ± 5
L*	99.1 ± 0.1	99.1 ± 0.1	99.2 ± 0.0	98.8 ± 0.1
a*	-0.52 ± 0.00	-0.60 ± 0.00	-0.61 ± 0.04	-0.54 ± 0.02
b*	4.39 ± 0.01	4.16 ± 0.24	4.30 ± 0.23	4.34 ± 0.20
C* <sub>ab</sub>	4.42 ± 0.01	4.20 ± 0.24	4.30 ± 0.24	4.34 ± 0.21
BI	4.80 ± 0.01	4.62 ± 0.26	4.76 ± 0.27	4.78 ± 0.21
h <sub>ab</sub>	96.83 ± 0.00	98.27 ± 0.40 <sup>b</sup>	97.98 ± 0.00 <sup>a,b</sup>	97.40 ± 0.00 <sup>a,b</sup>

Legend: SO<sub>2</sub>F: Free SO<sub>2</sub>; SO<sub>2</sub>T: Total SO<sub>2</sub>; TPC<sub>280nm</sub>: Total polyphenols content measured at 280 nm; GAE: Gallic acid equivalents; CE: (+)-Catechin equivalents; AA: Acetic acid; L\*: Lightness. a\*: Red/Green value. b\*: Blue/Yellow value; C\*<sub>ab</sub>: Chroma; BI: Browning index; h<sub>ab</sub>: Hue.

<sup>a b c</sup> Different superscript letters indicate a significant difference among the means in each row,  $p < 0.05$  by post hoc Tukey's test.

*flowTiO<sub>2</sub>-t0*, *GT-batchTiO<sub>2</sub>-t0*). Results showed that none of the process variables considered (namely filtration, continuous flow and the presence of TiO<sub>2</sub>) has significantly influenced the total polyphenols and acidity of wines, which confirmed previous findings (Patent No. 102018000004721; PCT/IB2019/053102). On the other hand, the Fe(III)/Fe(tot) ratio was found significantly higher in the *GT-beads-filtr-t0* possibly due to an oxygen uptake during the pumping of the wine into the flow device, and this results in an increased production of total peroxides (Table 3); contra, both the *GT-flowTiO<sub>2</sub>-t0* and the *GT-batch-TiO<sub>2</sub>-t0* experiments showed a non-significant Fe(III)/Fe(tot) increase compared to the *GT-filtr-t0* control. All these results, along with the different SO<sub>2</sub> consumption levels (Table 3) are consistent with the know redox reaction pathways of free sulfur dioxide in wine in the context of an oxygen supply (Sacks et al., 2020), except for samples containing TiO<sub>2</sub>, which seems to exert a protective effect both in batch and flow treatments. The removal of metal catalysts is not the cause of this effect, as indicated by the analysis of total iron: the (low) content of iron in wines was not significantly affected by the presence of TiO<sub>2</sub> material, showing that the sorbent material was not effective in metal adsorption. In the early stages of the patent development (Patent No. 102018000004721; PCT/IB2019/053102), the partial removal of transition metals by the adsorbent material was observed, but later studies have made the preliminary finding controversial. No remarkable differences were observed between wines according to CIELab parameters, except for the h<sub>ab</sub> which was found higher in the *GT-beads-filtr-t0*; this confirms further that the absence of TiO<sub>2</sub> is associated with a greater tendency to browning when wine is subjected to continuous flow. However, this effect is not evident in the BI, which remained substantially unchanged in the different wines.

Experiments in model wine solutions (Table 1, sample no. 8–10)

showed that only a limited amount of sorbent material can be released during the flow treatment and under oenological conditions. However, given the known photocatalytic effect of nanometric TiO<sub>2</sub> on organic substrates (Schneider et al., 2014), the post-treatment evolution of wines was studied by heating, to simulate an extended shelf-life and disclose any long-term effect of the protein stabilization treatment in the oxidative stability. Selected samples (*GT-beads-filtr*, as the control; *GT-flowTiO<sub>2</sub>*; *GT-batchTiO<sub>2</sub>*) were analyzed following a 20-days forced aging coupled to daylight exposure ('t20L' series), and dark ('t20D' series).

In general, the *GT-beads-filtr* samples retained the higher content in peroxides (Table 4), indices of prominent oxidative phenomena, regardless the presence/absence of light; at the same time, the oxidative onset did not show evident effects on flavan-3-ols, volatile acidity, and sulphates content, that can be traced back to TiO<sub>2</sub>-based treatments.

The CIELab colorimetric analysis of wines was implemented after the forced aging to identify distinctive chromatic characteristics related to the browning onset; the color substantially changed in the wines, with respect to the time zero (Table 3) and in relation to the different treatments (Table 4), until obtaining their peculiar grouping in the a\*b\* color diagram (Fig. 1). All samples showed h<sub>ab</sub> values in the angle defined between 92.25°-93.97°, thus generally approaching to the medium brownish-yellow tones (90°) more than the green (100°) (Table 4). Moreover, all wines have a high luminosity (L\*) ranging 97.4–98.4, probably due to the 0.45 µm CA filtration, which was performed in all samples simulating a pre-bottling filtering. The t0 samples, highlighted in red in Fig. 1, showed (non-significantly) higher L\*-values in the flow treated samples, possibly due to a retention of colloids and particulates during the treatment of unfinished wines.

The L\* values in *GT-batchTiO<sub>2</sub>* samples in wine were higher, along with lower chroma (C\*<sub>ab</sub>) values, and this informs that the oxidation in the wines was less pronounced were *TiO<sub>2</sub>-batch* treatment was applied, regardless the presence of light; on the opposite, L\* was lower and C\*<sub>ab</sub> markedly higher in the *GT-beads-filtr* wines, owing to the oxidative browning (Benucci et al., 2024), and in a similar extent in dark and light exposure. The *GT-flowTiO<sub>2</sub>* retained intermediate values in terms of color component when compared to batch samples, revealing the presence of further eliciting oxidation mechanisms, whose effect however is apparently mitigated by the presence of TiO<sub>2</sub>. Both BI and h<sub>ab</sub> confirm the same trend.

Regarding browning kinetics, the timecourse of the OD<sub>420nm</sub> for accelerated aging under light exposure and dark, highlighting a linear trend for the absorbance increase in time which is properly described by a zero-order kinetic rate (Fig. 2; Supplementary Material SM1). The zero-order kinetic model correctly describes those reactions whose rate is independent of the concentration of the reagents. In the case of wine, the oxidizing species (typically reactive oxygen species, ROS) and oxidizable substrates (i.e., ethanol, polyphenols) involved tend to regenerate in a certain extent; the presence and/or extent of catalysts may determine a variation in the kinetic pattern (Danilewicz, 2021). In this experiment, the adherence of wines to same kinetic models regardless the treatment and the light exposure, leads to deduce that even TiO<sub>2</sub> is involved in regeneration phenomena, or (more likely) that the TiO<sub>2</sub> eventually present does not significantly catalyze the oxidative process. Different kinetic rates (Supplementary Material SM1) resemble the tendency of TiO<sub>2</sub>-treated wine to delay oxidation which, on the contrary, proceeds more rapidly in the *GT-beads-filtr-t20L* and *GT-beads-filtr-t20D* samples. The experiment performed in dark reported low reproducibility against replicates for longer storage periods and regardless the sample treatment (Fig. 2), which appeared occasional and could have influenced the kinetic outcomes in a certain extent; nevertheless, it was evident that the combination of light / TiO<sub>2</sub> did not adversely affect the aging of wines, rather did the presence/absence of flow, resulting in an oxygen supply.

In general, the batch protein stabilization with TiO<sub>2</sub> (*GT-batchTiO<sub>2</sub>*) is effective while preserving the compositional integrity of the wine. Within the proposed innovative treatment, the pumping phase during

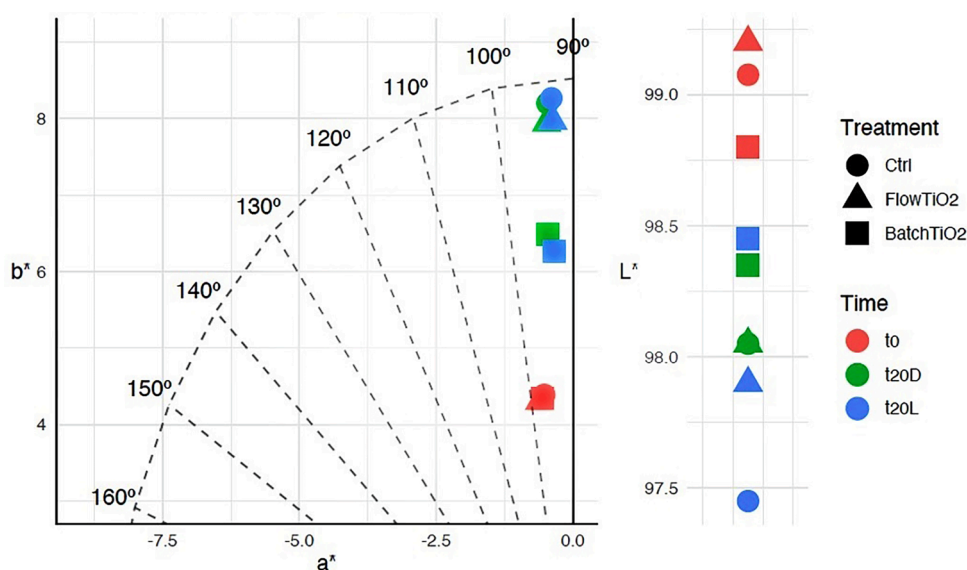
**Table 4**

Compositional profile of Gewürztraminer wines 2021 obtained immediately after the protein stabilization experiment (t0) and after 20 days of accelerated aging under light exposure (t20L) and dark (t20D).

	Light exposure			Dark		
	<i>GT-beads-filtr-t20L</i>	<i>GT-flowTiO2-t20L</i>	<i>GT-batchTiO2-t20L</i>	<i>GT-beads-filtr-t20D</i>	<i>GT-flowTiO2-t20D</i>	<i>GT-batchTiO2-t20D</i>
<b>Total peroxides</b> $\mu\text{M H}_2\text{O}$	0.42 $\pm$ 0.02 <sup>c</sup>	0.30 $\pm$ 0.00 <sup>a,b</sup>	0.29 $\pm$ 0.02 <sup>a</sup>	0.44 $\pm$ 0.02 <sup>c</sup>	0.35 $\pm$ 0.00 <sup>b</sup>	0.33 $\pm$ 0.03 <sup>a,b</sup>
<b>Flavan-3-ols</b> mg/L CE	16 $\pm$ 1	17 $\pm$ 4	21 $\pm$ 1	21 $\pm$ 3	19 $\pm$ 9	17 $\pm$ 0
<b>Volatile acidity</b> g/L AA	0.26 $\pm$ 0.00	0.25 $\pm$ 0.00	0.26 $\pm$ 0.01	0.26 $\pm$ 0.00	0.25 $\pm$ 0.01	0.26 $\pm$ 0.01
<b>Sulphates</b> mg/L $\text{SO}_4^{2-}$	533 $\pm$ 35	495 $\pm$ 8	451 $\pm$ 20	564 $\pm$ 41	523 $\pm$ 8	479 $\pm$ 21
<b>L*</b>	97.4 $\pm$ 0.1	97.9 $\pm$ 0.1 <sup>a,b</sup>	98.5 $\pm$ 0.1 <sup>b</sup>	97.6 $\pm$ 0.3	98.1 $\pm$ 0.1 <sup>a,b</sup>	98.4 $\pm$ 0.2 <sup>b</sup>
<b>a*</b>	-0.37 $\pm$ 0.01 <sup>b,c</sup>	-0.37 $\pm$ 0.02 <sup>b,c</sup>	-0.34 $\pm$ 0.01 <sup>c</sup>	-0.44 $\pm$ 0.00 <sup>a,b</sup>	-0.48 $\pm$ 0.01	-0.47 $\pm$ 0.04
<b>b*</b>	9.29 $\pm$ 0.30 <sup>b</sup>	7.97 $\pm$ 0.57 <sup>a,b</sup>	6.27 $\pm$ 0.10	9.45 $\pm$ 0.76 <sup>b</sup>	7.94 $\pm$ 0.50 <sup>a,b</sup>	6.49 $\pm$ 0.42
<b>C*<sub>ab</sub></b>	9.29 $\pm$ 0.30 <sup>b</sup>	7.98 $\pm$ 0.57 <sup>a,b</sup>	6.28 $\pm$ 0.10	9.46 $\pm$ 0.76 <sup>b</sup>	7.96 $\pm$ 0.49 <sup>a,b</sup>	6.51 $\pm$ 0.42
<b>BI</b>	10.06 $\pm$ 0.32 <sup>b,c</sup>	8.56 $\pm$ 0.63 <sup>a,b,c</sup>	6.67 $\pm$ 0.11	10.27 $\pm$ 0.87 <sup>c</sup>	8.60 $\pm$ 0.53 <sup>a,b,c</sup>	7.01 $\pm$ 0.49 <sup>a,b</sup>
<b>h<sub>ab</sub></b>	92.25 $\pm$ 0.00	92.54 $\pm$ 0.40	92.82 $\pm$ 0.00 <sup>a,b</sup>	92.82 $\pm$ 0.00 <sup>a,b,c</sup>	93.68 $\pm$ 0.41 <sup>b,c</sup>	93.97 $\pm$ 0.00 <sup>c</sup>

Legend:  $\text{SO}_2\text{F}$ : Free  $\text{SO}_2$ ;  $\text{SO}_2\text{T}$ : Total  $\text{SO}_2$ ; CE: (+)-Catechin equivalents; AA: Acetic acid; L\*: Lightness. a\*: Red/Green value. b\*: Blue/Yellow value; C\*<sub>ab</sub>: Chroma; BI: Browning index; h<sub>ab</sub>: Hue.

<sup>a b c</sup> Different superscript letters indicate a significant difference among the means in each row,  $p < 0.05$  by post hoc Tukey's test.



**Fig. 1.** ( $a^*b^*$ ) Color diagram and Luminosity ( $L^*$ ) of the Gewürztraminer wines (2021) before (t0) and after the accelerated aging (t<sub>20D</sub>, t<sub>20L</sub>).

the continuous process of protein stabilization contributes additional oxygen to the wine; nevertheless, according to the compositional profile of the *GT-flowTiO<sub>2</sub>* wines in the different trials (Table 3 and 4), the oxygen supply appears to be compensated by the presence of  $\text{TiO}_2$ . What was apparent from the oxidation tests was that no marked oxidation phenomena can be attributable to the contact of wines with  $\text{TiO}_2$ . On the contrary, experiments suggest a certain protective effect of the  $\text{TiO}_2$  treatment on the oxidative long-term stability of wine; in the 'batch' samples, where the flow process was not applied and therefore without additional oxygen inputs, performance in terms of oxidability was even improved.

Wine is a complex chemical matrix which components can be involved in many reaction mechanisms during storage and ageing. In particular, the oxidation of wine is known to be autoxidative, catalyzed by Fe and Cu ions, involves the Fenton chemistry and, especially in white wines, causes undesirable browning of phenolic compounds, triggered by  $\text{SO}_2$  (Sacks et al., 2020). Based on the experiments, it is necessary to further address the role of  $\text{TiO}_2$  in the framework of the oxidative stability of wine; in this view, the issue related to wine chemistry is further outlined based on bibliographic findings. Firstly, the mechanism of protein adsorption on  $\text{TiO}_2$ , which is the main objective of the flow treatment, adsorbs oxygen through a redox reaction, namely an electron transfer from the material to the protein - which adsorbs to the

ceramic surface in reduced form (Topoglidis et al., 2001b) - competing with the Fenton oxidative cascades. A further study demonstrated that  $\text{H}_2\text{O}_2$ , an important mediator of oxidative reactions in wines, tends to be deactivated through adsorption onto the  $\text{TiO}_2$  surface (Romanias et al., 2012). Further evidence from the literature with potentially detrimental effect of wine oxidability relates to the ability of  $\text{TiO}_2$  to adsorb  $\text{SO}_2$  (Ma et al., 2019), with a consequent deactivation and/or reduction in its protective effect. Nevertheless, this is reported as a photocatalytic reaction and can therefore be avoided by applying the continuous stabilization under appropriate darkness; this is easily achieved by using a device with stainless steel tubing. As a confirmation, the  $\text{TiO}_2$ -related depletion in sulfur dioxide was not observed in this experiment.

#### 4. Conclusion

In the present work, an innovative technology for the protein stabilization of white wines have been developed advantaging of a novel,  $\text{TiO}_2$ -based sorbent material in a continuous process. The technology has been patented and preliminary studies have shown its high industrial transferability potential as an alternative to batch treatment with bentonite, improving the environmental impact, and the management of the stabilization process. In this work several key issues have been addressed about the innovative technology, including (i) optimum

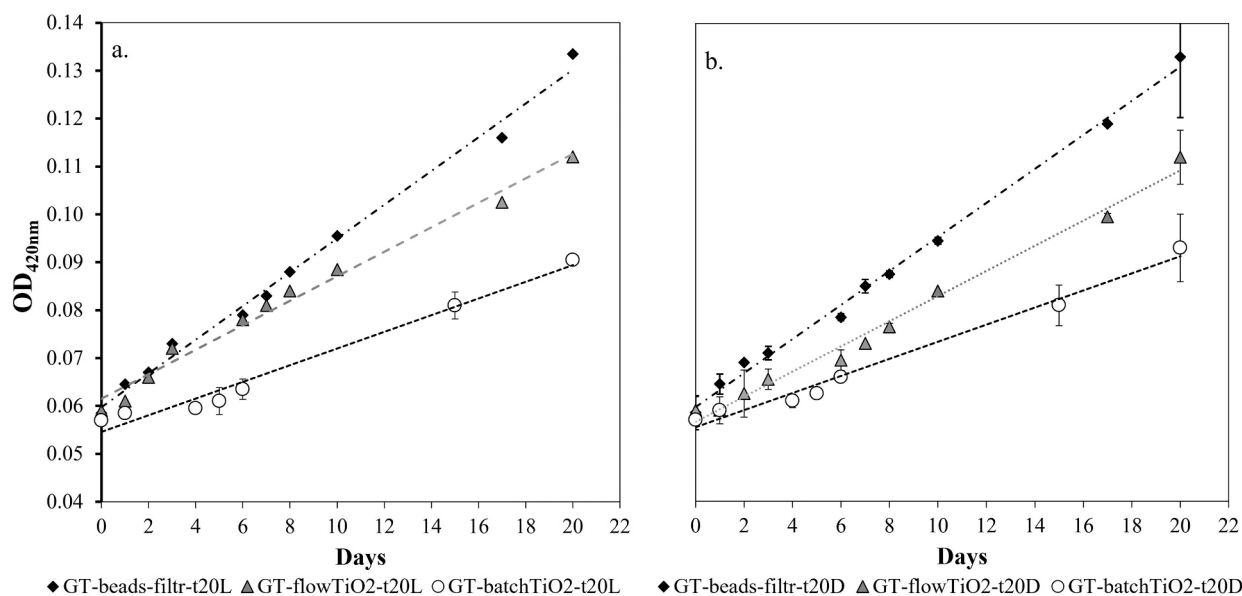


Fig. 2. Timecourse of the browning development ( $\Delta OD_{420nm}$ ) of Gewürztraminer wines 2021 during forced aging (20 days  $T = 35 \pm 1$  °C) under light exposure (a) and dark (b) conditions.

process parameters to enhance protein stability along with wine quality, (ii) the impact of boundary conditions, (iii) the extent of  $TiO_2$  released in the wine and (iv) and the short- and long-term impact of the treatment in the oxidative stability of wine. Samples and relevant controls were subjected to different experiment aimed at exploring the impact of the treatment in both standard and extreme conditions, with promising results in terms of adsorption selectivity, wine protein and oxidative stability; on this latter point, potential protective effects were highlighted that will require further investigation. In conclusion, results demonstrate a clear potential for technology transfer in the cellar, subject to verification of further parameters such as operating cycles, regenerating capacity and – more generally – the lifecycle assessment of the sorbent material. In addition, the protection form oxidation traced back to contact with  $TiO_2$  may offer additional benefits to the winemaking industry and deserves further investigation.

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#### CRedit authorship contribution statement

**Arianna Ricci:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Andrea Versari:** Conceptualization, Investigation, Methodology, Supervision, Validation, Writing – review & editing. **Luigi Ragni:** Formal analysis, Methodology, Resources, Supervision, Writing – review & editing. **Giuseppina P. Parpinello:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

Data will be made available on request.

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#### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foodchem.2024.138868>.

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